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[bestaccomplishment]The Ionospheric Dynamics and ElectroDynamics Data Assimilation (IDED-DA) model discovered new ionosphere phenomena, including a terminator current, plasma patches that are created in the polar cap, and a tongue-of-ionization the develops in the evening local time sector, not the noon sector.
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Consultant, Air Force Scientific Advisory Board

FINAL REPORT

Studies to Improve the Science in the GAIM - Full Physics Model

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LONG-TERM GOALS

The primary goals of the project are to conduct scientific studies to improve the science in the GAIM-Full Physics data assimilation model and to elucidate the processes underlying ionospheric weather features. The emphasis is on the effect that equatorial plasma bubbles have on data assimilation and on ways to improve the high-latitude ionosphere in the GAIM-FP model.

OBJECTIVES

We have two physics-based data assimilation models of the ionosphere that were used in a program called Global Assimilation of Ionospheric Measurements (GAIM). One of the data assimilation models is now in operational use at the Air Force Weather Agency (AFWA) in Omaha, Nebraska. This Gauss-Markov data assimilation model (GAIM-GM) uses a physics-based model of the ionosphere (IFM) and a Kalman filter as a basis for assimilating a diverse set of real-time (or near real-time) measurements. The second data assimilation model uses a physics-based Ionosphere-Plasmasphere Model (IPM) and an ensemble Kalman filter as a basis for assimilating the measurements. This full physics model (GAIM-FP), which covers the altitude range of from 90 to 30,000 km, is more sophisticated than the GAIM-GM model, and hence, should provide more reliable specifications in data-poor regions and during severe weather disturbances. Both GAIM models can assimilate several different data types, but both models only assimilate data at middle and low latitudes. However, we also developed a separate data assimilation model for the high-latitude Ionosphere Dynamics and Electrodynamics (IDED-DA), and this model can be used to improve the physics in GAIM-FP at high latitudes. The specific objectives are: (1) Accumulate statistics on the occurrence frequency and characteristics of equatorial plasma bubbles; (2) Construct semi-analytic models to describe both single and multiple bubbles for application in ionosphere simulation studies; (3) Conduct GAIM simulations both with and without plasma bubbles in order to quantify the effect of plasma bubbles on GAIM electron density reconstructions; (4) Investigate ways to either incorporate or eliminate measurements contaminated with plasma bubbles; (5) Study ways to use SCINDA scintillation data and C/NOFS satellite measurements in the GAIM-FP model; (6) Determine the uncertainties in the background physics-based model (IPM) due to uncertain parameters/processes; and (7) Conduct a series of simulations with

the high-latitude data assimilation model (IDED-DA) and compare the results with those obtained from current GAIM models in an effort to improve GAIM-FP.

APPROACH

Our approach is to use three data assimilation models (GAIM-GM, GAIM-FP, and IDED-DA) and the physics-based Ionosphere-Plasmasphere Model (IPM) to accomplish the goals and objectives outlined above.

The Gauss-Markov data assimilation model (GAIM-GM) was used as part of the GAIM program (*Schunk et al., 2004a, 2005a; Scherliess et al., 2004, 2005, 2006*). It is based on the Ionosphere Forecast Model (IFM) (*Schunk*, 1988; *Sojka*, 1989; *Schunk et al.,* 1997), which covers the E-region, F-region, and topside ionosphere up to 1400 km, and takes account of five ions (NO^+, N_2^+, O_2^+, O^+, H^+). In GAIM-GM, the ionosphere densities obtained from the IFM are combined with the measurements via a Kalman filter technique. The model has both global and regional modes. GAIM-GM can assimilate GPS/TEC from up to 1000 ground receivers, in situ N_e from 4 DMSP satellites, bottomside N_e profiles from 80 digisondes, occultation data from satellites (IOX, CHAMP, SAC-C, COSMIC), and UV emission data from the SSUSI and SSULI instruments (*Scherliess et al., 2005; Sojka et al., 2007; Thompson et al., 2006*).

The full physics data assimilation model (GAIM-FP) rigorously evolves the ionosphere and plasmasphere electron density field and its associated errors using the full physical model (*Schunk et al.,* 2004b, 2005b*; Scherliess et al*., 2004, 2005). Advantages of this rigorous approach are expected to be most significant in data-sparse regions and during times of "severe weather." GAIM-FP is based on a new physics-based Ionosphere-Plasmasphere Model (IPM), which is state-of-the-art and includes six ion species (NO^+, O_2^+, N_2^+, O^+, He^+, H^+), ion and electron temperatures, and plasma drifts parallel and perpendicular to the geomagnetic field. The IPM uses the International Geomagnetic Reference Field, which accurately describes the relative positions of the geographic and geomagnetic equators and the declination of the magnetic field lines. The IPM covers the altitude range from 90 to 30,000 km, which includes the E-region, F-region, topside ionosphere, and plasmasphere. In GAIM-FP, the IPM electron densities and the different data sources are combined via an ensemble Kalman filter technique. The GAIM-FP model provides 3-dimensional plasma densities as a function of time, self-consistent distributions for the global drivers (neutral winds and densities and equatorial electric fields), and quantitative estimates for the accuracy of the reconstructed plasma densities.

The IDED-DA model is a physics-based, ensemble Kalman filter model for the high-latitude ionosphere and electrodynamics that can account for rapid time variations (~min) and small spatial scales (~50 km). The IDED-DA data assimilation model is based on three physics-based models (M-I electrodynamics, ionosphere, and magnetic inversion). The ionosphere model is a high-resolution version of the Ionosphere Forecast Model (IFM). The main electrodynamics inputs to the IFM are the plasma convection and precipitation patterns, which are obtained from the M-I electrodynamics model. The IFM calculates global distributions for plasma densities (N_e, NO^+, O_2^+, N_2^+, O^+, H^+), temperatures, and velocities. The M-I electrodynamics model is a high-resolution (10 km), time-dependent (5 sec) model of M-I coupling at high latitudes (*Zhu et al., 1993, 2000, 2005*). The model is based on a numerical solution of the MHD transport equations and Ohm's Law, with height-integrated Hall and Pedersen conductivities obtained from the IFM. The model calculates currents, particle precipitation and electric fields. The magnetic inversion model takes a 3-D current system as an input and calculates

the associated $\Delta\mathbf{B}$ in space and on the ground. The three physics-based models are used with an ensemble Kalman Filter to assimilate SuperDARN radar velocities, in situ velocities from the DMSP satellites, and $\Delta\mathbf{B}$ from both ground and satellite magnetometers. The output of the IDED-DA model is a full set of self-consistent, time-dependent plasma and electrodynamics parameters for the high-latitude regions, including electric potential, convection electric field, energy flux and average energy of precipitation, field-aligned and horizontal currents, Hall and Pedersen conductance, Joule heating rates, ground and space magnetic disturbances, and 3-D plasma densities, drifts, and temperatures.

WORK COMPLETED

During the project, we worked on the following tasks:

(1) The high-latitude IDED-DA model was run with varying amounts of magnetometer data, SuperDarn radar line-of-sight velocities, and DMSP satellite cross-track velocities. Simulations were conducted for quiet and storm conditions, for propagating plasma patches, and for different solar and seasonal conditions. The ionospheric density, electric field, and particle precipitation reconstructions obtained from the IDED-DA were far superior to those currently obtained from the GAIM-GM and GAIM-FP models, which are driven by empirical E-field and particle precipitation models. The IDED-DA results displayed sharp spatial gradients, rapid temporal variations, and realistic high-latitude features, in agreement with measurements. Therefore, the eventual coupling of IDED-DA to GAIM-FP will greatly improve the high-latitude representation in GAIM-FP.

(2) A graduate student, Janelle Jenniges, conducted IPM simulations in order to determine the sensitivity of the model output to important uncertain processes, including the O^+ - O collision frequency, nighttime ExB drifts, tidal forcing from the lower atmosphere, and secondary electron production in sunlight. This study was needed because the output from the IPM dominates the GAIM-FP reconstructions in regions far from data sources. The uncertain parameters/processes in physics-based models like the IPM can lead to more than a factor of 2 uncertainty in N_mF_2 in the equatorial anomaly. Therefore, reliable data sources are needed in critical global regions, both for practical applications and to elucidate important physical processes.

(3) A graduate student, Ken Fenton, conducted a series of GAIM-GM simulations including plasma bubbles in order to quantitatively determine the effect of plasma bubbles on the 3-D electron density reconstructions. The plasma bubbles were imposed on the IFM output using a semi-analytic bubble representation and then synthetic slant TEC values were obtained between the locations of real ground receivers and the GPS satellites. Next, the synthetic slant TEC values were assimilated in the GAIM-GM model and an ionospheric reconstruction was obtained. A GAIM-GM reconstruction was also obtained for the no-bubble case and the difference in the results showed the effect of plasma bubbles, which was to produce a broad area of erroneously low and smooth electron densities.

(4) Plasma bubbles are more detrimental to GAIM-FP than to GAIM-GM because GAIM-FP calculates the *self-consistent,* global distributions for N_e and ionospheric drivers (electric fields, neutral winds, and neutral composition). Because the drivers are obtained with GAIM-FP, the N_e altitude profiles and gradients are generally much better than those obtained from GAIM-

GM. However, since the drivers are obtained, GAIM-FP is now sensitive to physics not included in the model (e.g., spread F and bubbles). For example, if plasma bubbles exist and GAIM-FP is not aware of them, it will try to accommodate the N_e depletions by erroneously adjusting the drivers (neutral winds and electric fields). Therefore, a graduate student, Omar Nava, studied the effect that equatorial plasma bubbles have on GPS-TEC measurements, so that measurements contaminated by bubbles could be eliminated before assimilation. The study was conducted with synthetic bubbles and synthetic GPS-TEC data. In particular, the Ionosphere Forecast Model (IFM) was used to conduct time-dependent global simulations for a wide range of solar, seasonal, and geomagnetic conditions, and for numerous bubble configurations (height, depth, width, and spacing). From the 405 cases considered, azimuth and elevation look angles of slant TEC to the GPS satellites were determined that did not intersect the plasma bubbles, which is information needed for GAIM-FP. For the slant GPS-TEC paths that intersected the plasma bubbles, the quantitative effect of the bubbles on slant TEC was determined.

(5) An SED is a narrow ridge of enhanced ionization that can extend over the United States from Florida to the Great Lakes. It first appears near the southern tip of Florida at sunset during a geomagnetic storm. It then moves northward at about 1 km/s until the ridge is completely formed. The ridge of ionization typically is 600 to 1000 km wide, has a peak altitude of 500 km, and lasts 2-5 hours. Because a SED affects GPS/TEC correction maps, which are needed for geo-location, a graduate student, Lindon Steadman, conducted an extensive series of GAIM simulations in order to determine how many ground GPS receivers are needed in the United States in order to properly account for SEDs. He also determined the minimum number and optimum placement of the ground receivers for a given resolution. This information is generally useful in any area of the globe where plasma density structures occur.

(6) The high-latitude data assimilation model (IDED-DA) was run for quiet, storm and substorm conditions in order to study the formation of plasma patches, the entry of plasma into the polar cap through the cusp, and southward-to-northward changes in the Interplanetary Magnetic Field (IMF). The goal was not only to study these features, but also to see the impact of different data types, including magnetometer data, SuperDarn radar line-of-sight velocities, and DMSP satellite cross-track velocities. The first step was to conduct all studies with only 40 – 60 ground magnetometers and ACE satellite data, and this step was completed. The IDED-DA model was run with a 10-second time step and a 5-minute data assimilation step.

(7) A graduate student, David Broadwater, conducted GAIM simulations in order to determine the accuracy of GAIM electron densities at the altitude of the International Space Station (ISS), which varies from 350-450 km. In-situ electron densities measured along the ISS orbit were compared with those obtained from several ionosphere models, including empirical, physics-based, and GAIM models. The data assimilated in GAIM included GPS/TEC measurements, ionosonde bottom-side N_e profiles, and in-situ N_e densities at 800 km obtained from the DMSP satellites. An M.S. Thesis describing this work was published in March 2013.

(8) A graduate student, Jeremy Hromsco, is conducted GAIM simulations in order to determine the sensitivity of the GAIM model to solar and magnetic activity. The sensitivity of the model to these conditions was expected to vary depending on the amount of data assimilated. Therefore, the plan was to assimilate different data amounts and consider a range of geophysical conditions. An M.S. Thesis describing this work has been published in March 2014.

(9) The graduate student involvement in this research was the result of a collaborative effort between members of the USU GAIM team and faculty members (Lt. Col. A. Acebal and Dr. W. Bailey) at the Air Force Institute of Technology.

RESULTS

Plasma Bubbles

A graduate student, Omar Nava, studied the effect that equatorial plasma bubbles have on GPS-TEC measurements. The study was conducted with synthetic bubbles and synthetic GPS-TEC data. In particular, the Ionosphere Forecast Model (IFM) was used to conduct time-dependent global simulations for 27 geophysical conditions that cover a wide range solar cycle, seasonal, and geomagnetic activity conditions. For each geophysical condition, different plasma bubble configurations were imposed on the time-dependent, global, ionospheric output. In each bubble scenario, a series of bubbles was imposed at 1800 local time. The bubbles were imposed one at a time with spaces between them as the Earth rotated, so that 10 identical equally-spaced plasma bubbles existed throughout the night. For each of the 27 geophysical conditions, 15 plasma bubble configurations were considered, including bubbles with factors of 10, 100, 1000 depletions and bubbles with apex altitudes of 3000, 3500, 4000, 4500 and 5000 km. This resulted in a total of 405 cases. Next, ground-based GPS receivers were placed at five longitudes (30°, 90°, 195°, 270°, 315°) and at latitudes from -24° to $+24^\circ$ geomagnetic with an 8° separation along each longitude (Figure 1). Subsequently, for the different geophysical cases and bubble scenarios, azimuth and elevation look angles of slant TEC to the GPS satellites were determined that did not intersect the plasma bubbles, which is information needed for GAIM-FP. For the slant GPS-TEC paths that intersected the plasma bubbles (Figure 2), the quantitative effect of the bubbles on slant TEC was determined.

Figure 3 shows depletion ratios for solar maximum – summer conditions for a ground GPS site on the magnetic equator in the African sector (see Figure 1). The depletion ratio is defined to be (normal slant TEC – bubble slant TEC)/normal slant TEC, where 'normal slant TEC' corresponds to the IFM simulation without bubbles and 'bubble slant TEC' is the corresponding IFM case with bubbles. If a slant TEC path misses bubbles in the IFM run with bubbles, then the depletion ratio is 0 (no bubble influence). On the other hand, a complete bubble influence yields a depletion ratio of 1. The vertical lines in Figure 3 represent slant TEC paths from the ground location (magnetic equator in the African sector) to the GPS satellites. Fifteen different bubble scenarios are shown. Similar plots were obtained for different solar cycle and seasonal conditions, and for all of the ground locations in the 5 regional sectors (Figure 1). This information is important for producing a probability map of when slant GPS/TEC paths could intersect plasma bubbles. Note that if bubble data are assimilated in GAIM-FP without knowledge, completely erroneous electric field and neutral winds will be obtained from the ensemble Kalman filter.

Ionosphere-Plasmasphere Model Studies

A graduate student (Janelle Jenniges) studied the effect that different physical assumptions can have on global models of the electron density distribution. The model used in this study was the Ionosphere Plasmasphere Model (IPM), which is a physics-based, time-dependent, global model that uses empirical models for the neutral atmosphere (MSIS) and neutral wind (Horizontal Wind Model, HWM). The IPM extends from 90 – 30,000 km, allows for inter-hemisphere plasma flow, includes six

ion species (NO^+, $O2^+$, $N2^+$, O^+, H^+, He^+), and is based on the International Geomagnetic Reference Field (IGRF). The physical parameters studied include the O^+/O collision frequency, zonal wind, secondary electron production, nighttime E x B drifts, and tidal structure (Table1, first column). The uncertainty associated with each parameter was determined by comparing a default run of the IPM (Table 1, second column) to a run with the parameter adjusted within an allowable range (Table 1, third column). The parameters were studied separately and the evaluations were conducted for a range of solar and seasonal conditions. The fourth column in Table 1 shows the variations in Total Electron Content (TEC)/peak electron density (N_mF_2) that result from the uncertainty in the listed parameters. A factor of 2 uncertainty in the O^+ - O collision frequency results in a 30 – 240 % uncertainty in TEC/N_mF_2. Figure 4 shows plots of the percentage difference in the calculated electron densities due to a factor of 2 uncertainty in the O^+ - O collision frequency. The density differences are shown via altitude-latitude plots at 0^o E longitude for solar minimum, December and low Kp. Increasing the O^+ - O collision frequency by a factor of 2 above its default value leads to enhanced electron densities at night (04 – 08 LT) in and above the F-region and decreased electron densities below the F-region. With an enhanced O^+ - O collision frequency, the upward wind-induced plasma drift is increased and this acts to decrease the electron densities below the F-region. This upward transport of plasma, coupled with the slower rate of downward diffusion (due to the enhanced collision frequency) accounts for the elevated electron densities in the F-region.

The uncertainties in the other parameters listed in Table 1 also resulted in large uncertainties in the calculated electron densities. In particular, the zonal winds near the magnetic equator that are obtained from the HWM are not accurate and to determine their effect, IPM simulations were conducted with the zonal wind set to zero. This resulted in electron density changes as large as 400 %. The uncertainty in the daytime production of secondary electrons (17 – 33 %) acts to produce a similar uncertainty in TEC/N_mF_2. The nighttime, downward, ExB drifts obtained from the Scherliess-Fejer equatorial drift model are too large when used in the IPM; that is, the IPM electron densities do not agree with measurements when the Scherliess-Fejer empirical model is used. The downward drifts had to be reduced as a function of F10.7 and the change in nighttime TEC/N_mF_2 varied from 160 – 630 %. Finally, the downward ExB drifts were modulated so that the IPM simulations could include the 4-wave signature in TEC/N_mF_2 that is associated with wave coupling between the lower and upper atmosphere. The variations in TEC/N_mF_2 associated with the 4-wave signature are from 11 – 23 %.

The important basic result obtained from the above study is that global physics-based models of the thermosphere-ionosphere-plasmasphere system do not have sufficient accuracy for space weather applications. Also, the large uncertainty associated with these models means that it will be difficult to draw unique conclusions about the importance of complex physical processes from model – measurement comparisons.

IDED-DA Simulations

The high-latitude data assimilation model (IDED-DA) was run for quiet, storm and substorm conditions in order to study the formation of plasma patches, the entry of plasma into the polar cap through the cusp, and southward-to-northward changes in the Interplanetary Magnetic Field (IMF). The goal was not only to study these features, but also to see the impact of different data types, including magnetometer data, SuperDarn radar line-of-sight velocities, and DMSP satellite cross-track velocities. The first step was to conduct all studies with only 40 – 60 ground magnetometers and ACE satellite data. The IDED-DA model was run with a 10-second time step and a 5-minute data assimilation step. In the course of these studies, we obtained some very interesting and new dynamical

features. These include: (1) A field-aligned current along the solar terminator due to the conductivity gradient, (2) The break-up of a stable tongue-of-ionization into plasma patches in the polar cap during a northward IMF excursion, (3) A plasma tongue-of-ionization the originates from the 1800 local time sector, (4) Precipitation oval bifurcation during storms, and (5) High-resolution substorm dynamics. Two examples are given in what follows.

We simulated the December 17, 2001 period, which contained a long period of southward IMF followed by a northward IMF excursion. The 2-cell plasma convection pattern remained stable for several hours and this resulted in a stable tongue-of-ionization that extended across the polar cap from the sunlit noon sector toward midnight (Figure 5, left column). However, the IMF turned northward at about 1700 UT, which resulted in a convection disruption and caused the tongue-of-ionization to break up into plasma patches in the polar cap (Figure 5, right column).

The solar terminator is typically equatorward of the polar region for most of the day in winter. At these times, the solar terminator does not affect the electron precipitation and associated current in the cusp (Figure 6, left column). However, as the terminator merges with the high-latitude auroral region, the conductivity gradient associated with the terminator induces a field-aligned current, and the upward field-aligned current associated with the terminator acts to expand the region of electron precipitation (Figure 6, right column).

IMPACT/APPLICATIONS

The USU GAIM-GM and GAIM-FP data assimilation models provide ionosphere specifications and forecasts on both global and regional grids. These specifications and forecasts are useful for DoD and civilian command and control operations, including HF communication links, geo-locations, over-the-horizon (OTH) radars, surveillance, and navigation systems that use GPS signals.

TRANSITIONS

The latest version of the operational GAIM-GM model (Version 3.1.0) was delivered on October 16, 2013 and the first version of the GAIM-FP model was delivered in February 2014. The GAIM models are running at NRL, AFRL and AFWA.

RELATED PROJECTS

This project is associated with a previous basic research DoD MURI program called Global Assimilation of Ionospheric Measurements (GAIM). Rudimentary research grade (scientific) versions of our GAIM data assimilation models were developed/improved under the MURI program.

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HONORS/AWARDS/PRIZES

R. W. Schunk was elected a Member of the International Academy of Astronautics (7 July 2011).

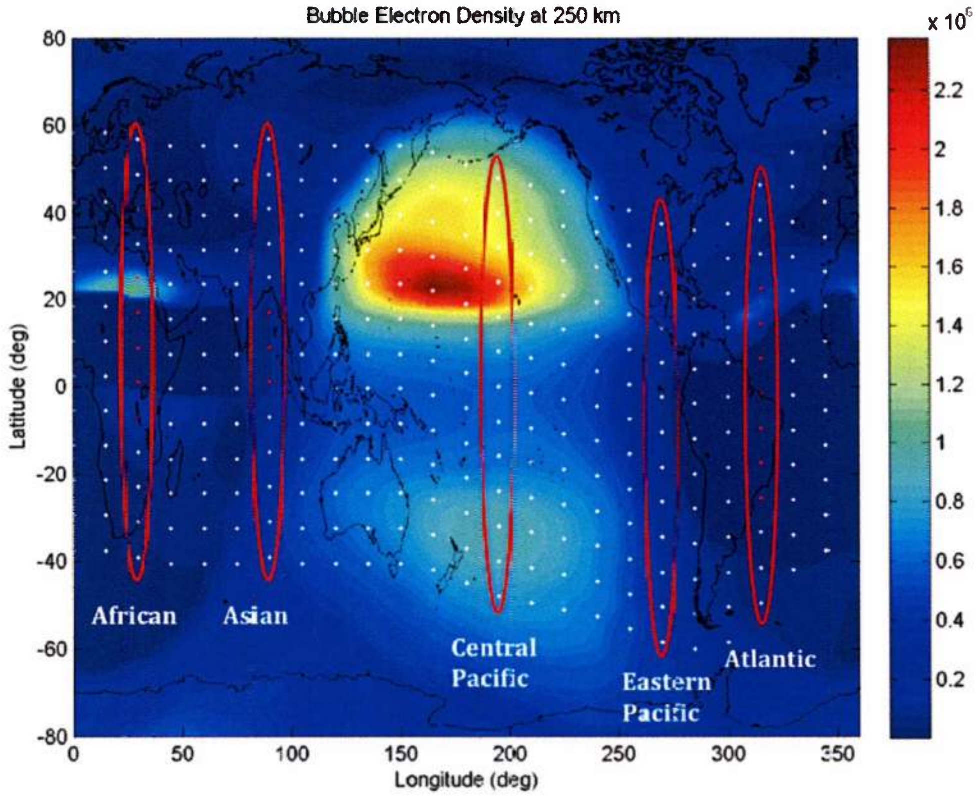


Figure 1. Locations of ground GPS receivers in five regional sectors for the bubble depletion study. From Omar Nava.

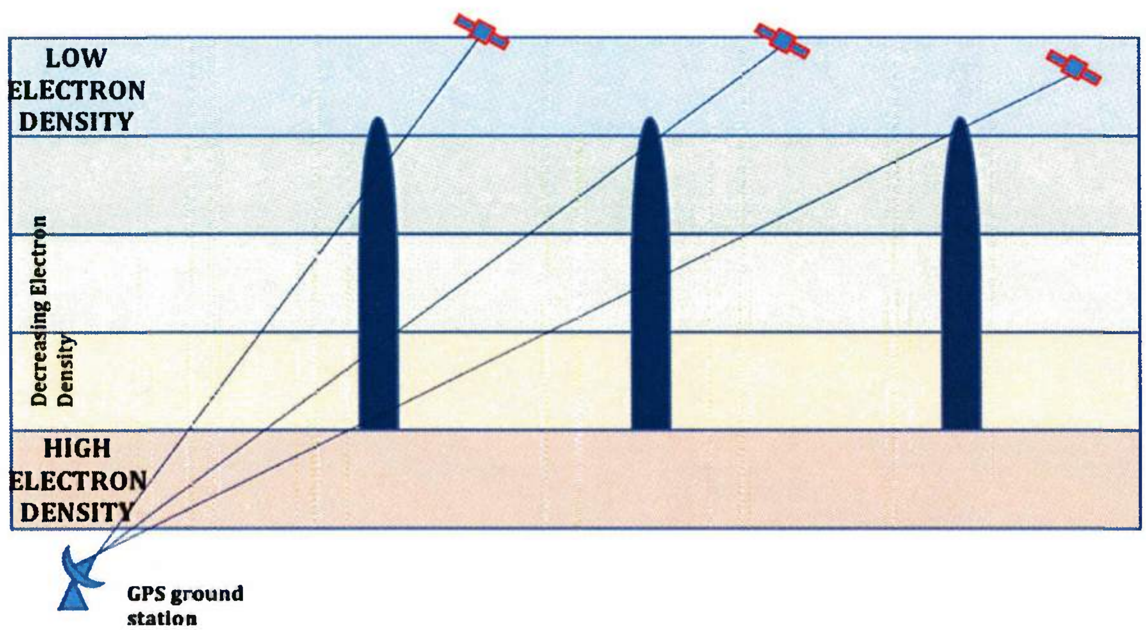
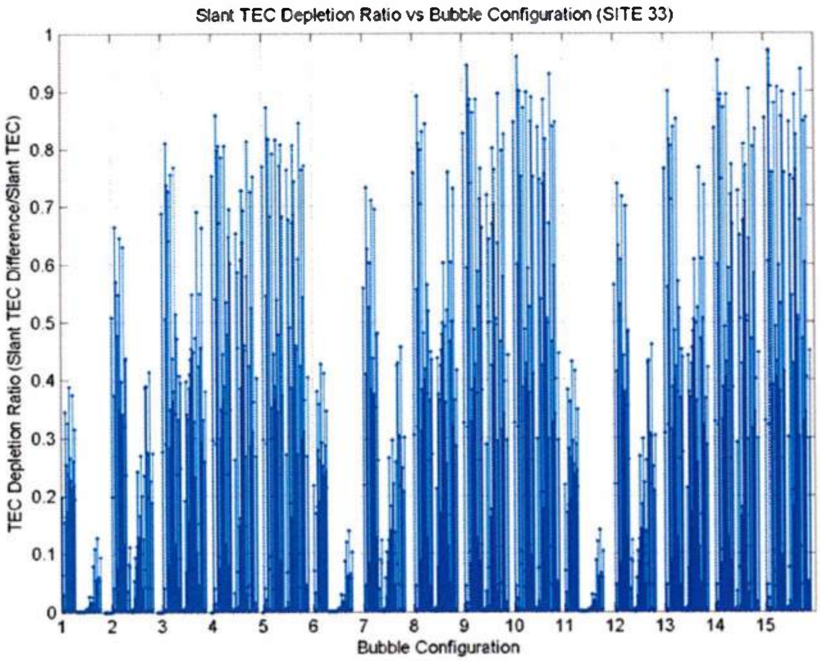


Figure 2. Schematic diagram of slant GPS/TEC paths intersecting plasma bubbles. From Omar Nava.

Region I – African (Max, Sum)



Bubble Configuration

1 – 3000 km, 10x
2 – 3500 km, 10x
3 – 4000 km, 10x
4 – 4500 km, 10x
5 – 5000 km, 10x
6 – 3000 km, 100x
7 – 3500 km, 100x
8 – 4000 km, 100x
9 – 4500 km, 100x
10 – 5000 km, 100x
11– 3000 km, 1000x
12 – 3500 km, 1000x
13 – 4000 km, 1000x
14 – 4500 km, 1000x
15 – 5000 km, 1000x

Figure 3. Depletion ratios for slant TEC paths from a ground location (magnetic equator, African sector) to the GPS satellites. Results from fifteen different bubble scenarios are shown. From Omar Nava.

Parameter	Default	Adjustment	TEC/N_mF_2 Effect
O^+ - O coll freq	Factor of 1	Factor of 2	30 – 240 %
Eq zonal wind	HWM Winds	0 zonal wind	50 – 400 %
Ne daytime prod	Standard	17 – 33 %	17 – 33 %
Night ExB drifts	Scherliess ExB	Decrease vs F10.7	160 – 630 %
Tidal Forcing	None	4 – wave via ExB	11 – 23 %

Table 1. Uncertain parameters (first column), default values (second column), adjustments (third column), and the effect on TEC/N_mF_2. From Jenniges (2011).

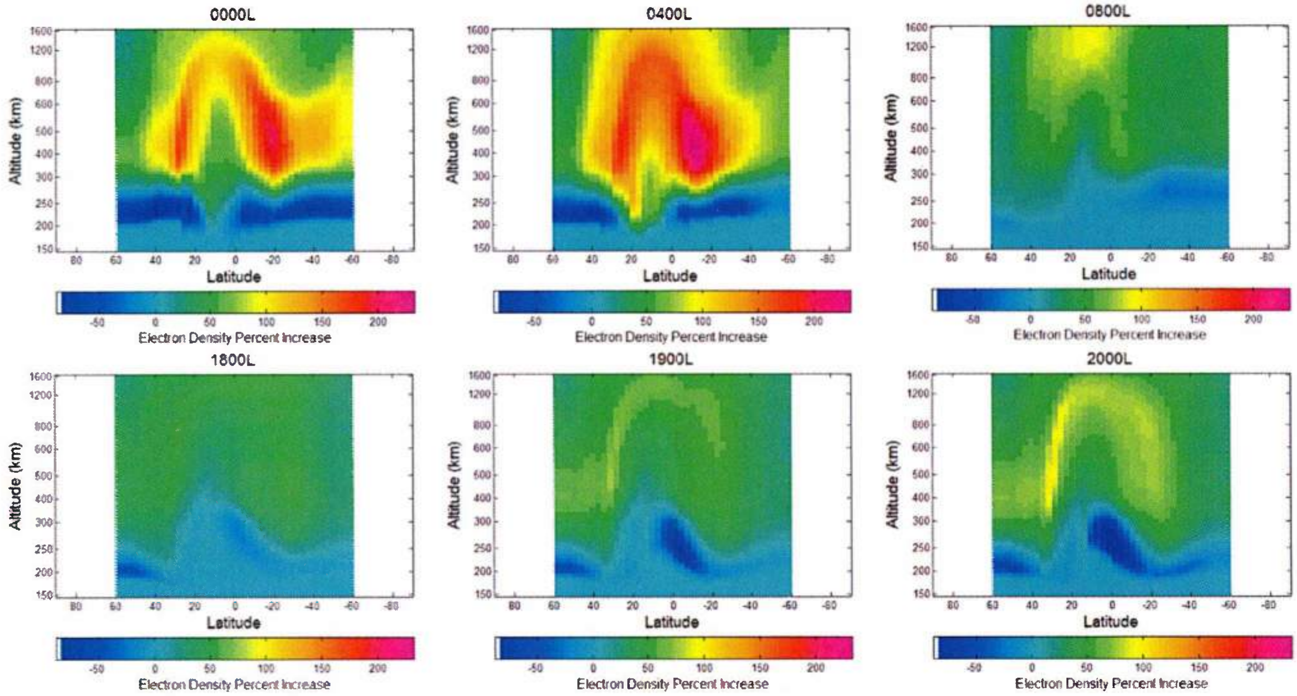


Figure 4. Percentage difference in the calculated electron densities due to a factor of 2 uncertainty in the O^+ - O collision frequency. The density differences are shown versus altitude and latitude at 0° E longitude and at selected times. The results are for solar minimum, December and low Kp conditions.

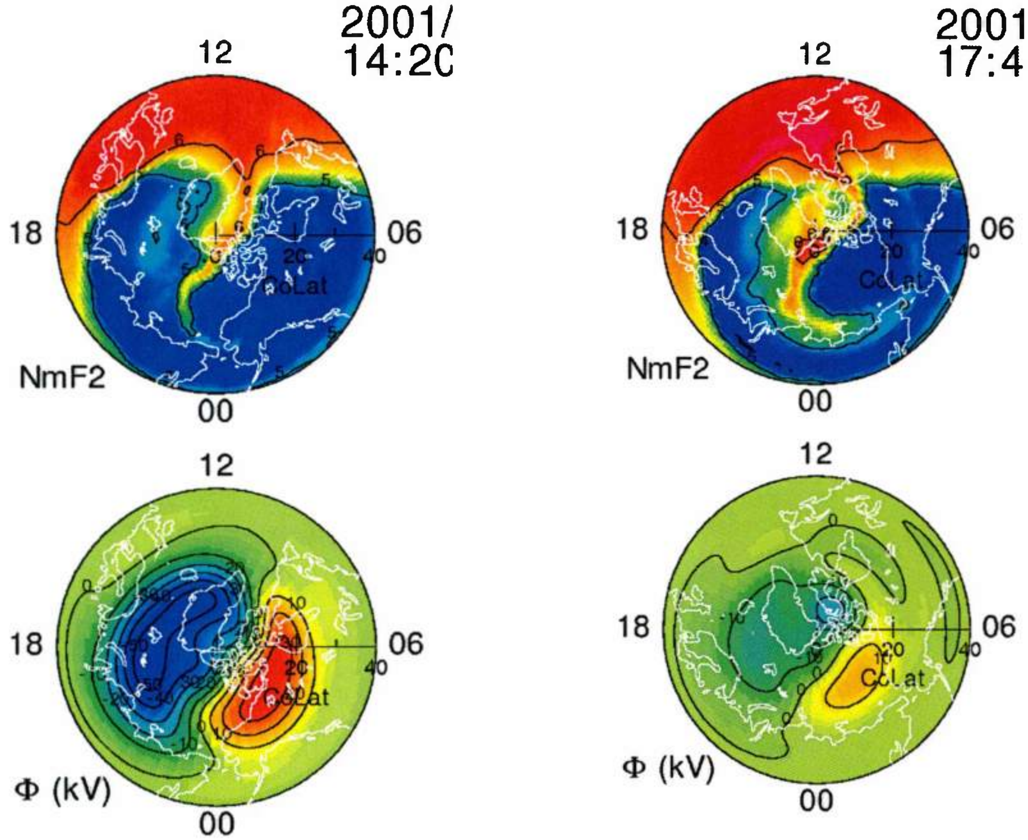


Figure 5. Snapshots of peak electron densities (top) and plasma potential patterns (bottom) at 14:20 UT (left) and at 17:40 UT (right). The top-left dial shows a stable tongue-of-ionization and the top-right dial shows a break-up of the tongue during a northward turning of the IMF. The tongue breaks up when the potential pattern becomes disrupted.

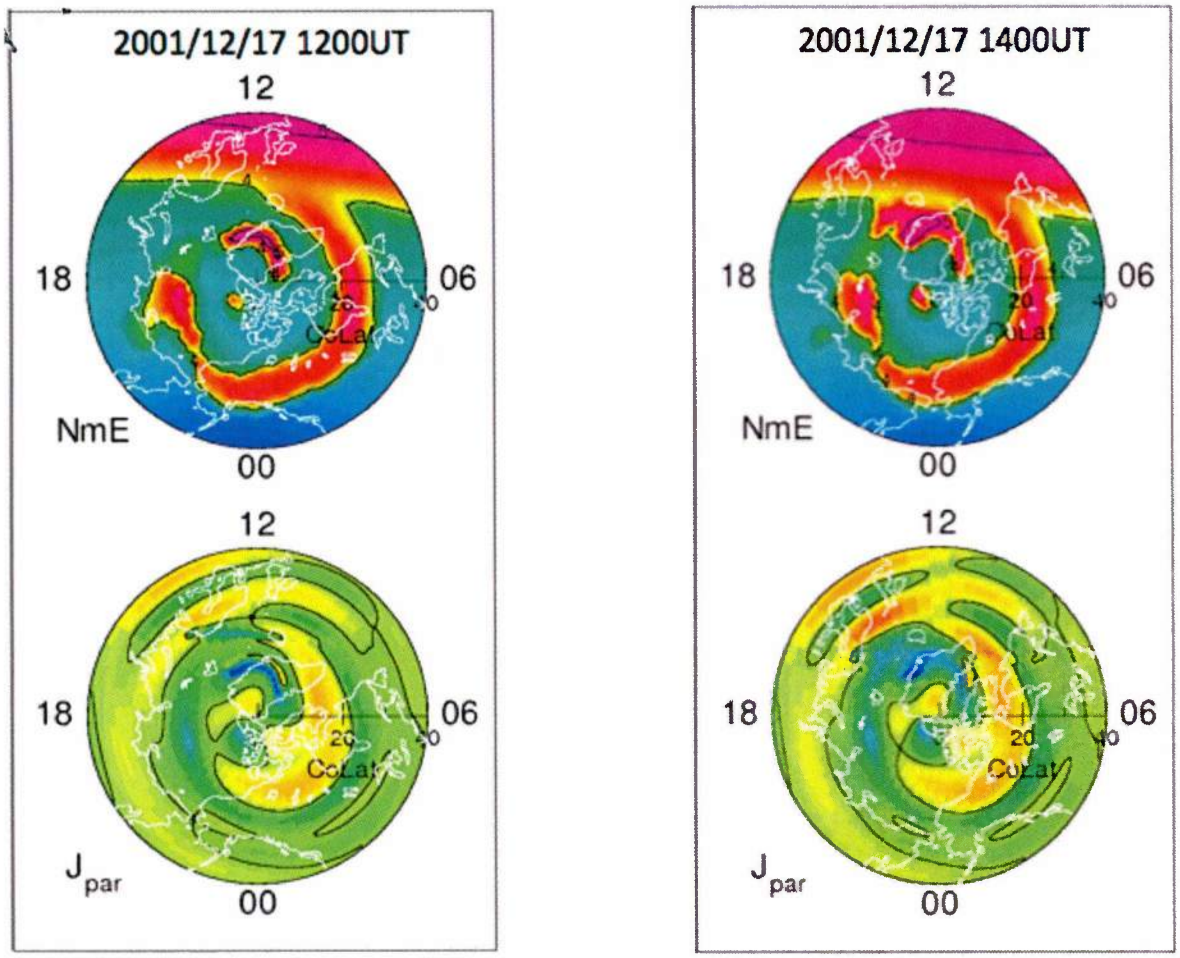


Figure 6. Snapshots of peak E-region densities (top) and field-aligned currents (bottom). When the terminator does not intersect the auroral oval (left), the cusp is a distinct feature with the enhancement in E-region density and associated field-aligned current (blue area) clearly evident. When the terminator intersects the cusp (right), the precipitation and field-aligned current (blue area) are expanded. This occurs because the conductivity gradient associated with the terminator induces a field-aligned current.